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13. ABSTRACT *(Maximum 200 words)*

Capillary optics which use total external reflections to transmit x rays have been shown to have significant advantages in scatter reduction and resolution improvement in mammographic applications. The purpose of the proposed work is to perform lens simulations and image artifact elimination as part of the work of capillary optical mammography research. During the first year of the task, a lens simulation extended from the previous single fiber simulation has been implemented, a lens for the protocol mammography system has been re-measured in an extended energy range and analyzed with the program. The simulation has been proved to be helpful in understanding the lens performance. To observe the effects of artifacts on resolution, the Modulation Transfer Function (MTF) should be measured. MTF is the most fundamental measurement of spatial resolution used in radiology. Non-uniform transmission introduces difficulties in MTF measurement. A technique to measure MTF by taking an edge image and subtract the background has been developed. However, at the present time, the processed result was better than the expected ideal case for some unknown reasons. Further work is needed to find out the reason for this disagreement.

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Lei Wang　　　Sept 29, 98

PI - Signature　　　Date

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Introduction

At the present time the best way to fight breast cancer is through early detection. The size of malignancies in the early stage is very small, and the absorption of x rays by the malignancies and the breast tissue is similar. Thus high contrast and good resolution are especially important in mammography. In current digital mammography systems, contrast loss occurs from scattered x rays that strike the detector from all directions, and resolution is limited by the pixel size of the digital detector for computed radiography phosphor plates (CR plates), or the conversion efficiency and total number of pixels for visible light CCD systems.

Capillary x-ray optics use total external reflection to guide x rays through tiny hollow glass tubes, similar to the way conventional fiber optics transmit light. A capillary lens is a bundle of hollow glass tubes with channel sizes as small as few microns. The critical angle for total external reflection is as small as a few mrad (1.5mrad for 20 keV photons).[1,2] A capillary lens can provide almost total scatter rejection. A well-designed lens can also provide magnification without image degradation from a finite source spot size. Thus the effective resolution can be improved while a CR plate is used. Capillary optics can also demagnify the image to match a direct area detector, such as a CZT detector[3,4], which maybe available in the near future. Unlike the fiber-optic-CCD combination, this system does not involve the use of a phosphor to convert the x rays to visual light. The solid state detector can provide almost 100% quantum efficiency.

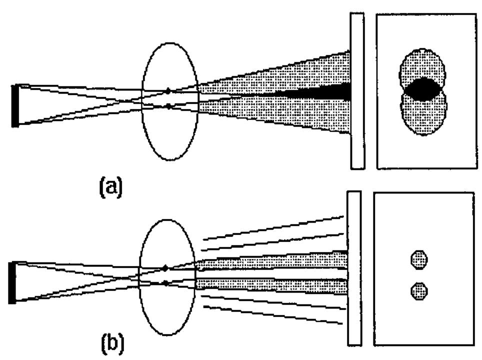

Figure 1 a) Image blurring in normal airgap magnification. b) Capillary lens between the patient and detector eliminates the focus spot bluring.

Capillary optical mammography has been cooperatively investigated by Center for X-ray Optics at University at Albany and the Radiology Dept. of University of Wisconsin for many years. Previous work has demonstrated the bright future of capillary optics in digital mammography with both contrast and resolution improvement.[5,6] Among the problems found in the previous work are the small size of the lens and non-uniform transmission. Artifacts caused by non-uniformity of transmission were observed in the image. Eliminating artifacts by image processing may be a better and more economic way than fabricating an ideal lens. Low reproducibility can be a problem in lens manufacture. It is extremely important to design a large lens by combining several small pieces. So a better understanding of lens behavior is necessary. Theoretical simulation has been proved to be very helpful in understanding the capillary and lens behavior, and provide feedback to the manufacturing process.[7]

The proposed work is focused on computer simulations and artifact elimination with image processing. It is the first year of a three-year grant. During the first year of the work, a lens simulation has been developed and applied to the experimental data. The simulation has proved to be helpful to understand the lens behavior. MTF is usually measured by taking an image of a slit. It is difficult to measure a stationary lens with this method when the transmission of the lens is not uniform. A method to measure MTF by taking an edge image was developed with background deduction technique. However, for unknown reason, it was found that the measured result was not consistent with the result from a scanning lens system. Further study is needed.

Body

Lens Simulation and Measurement

Simulation Geometry

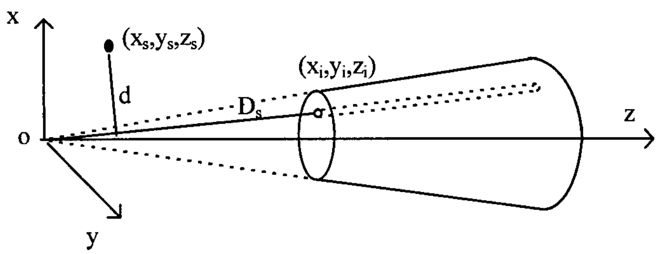

Figure 2 Sketch of the linear lens simulation geometry.

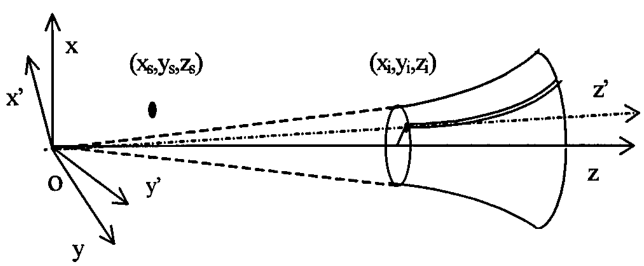

Figure 3 Sketch of the uniformly bent lens simulation geometry.

A geometrical simulation program for single capillaries has been developed by the author.[7,8] The transmission through hollow glass capillaries is simulated by tracing a large number of x rays through the capillary. The code includes the surface roughness[9] and waviness correction of the glass surface. The waviness correction is simulated as a random tilt of the glass wall in each reflection. The simulations point out that roughness is only important for low energy photons while waviness has more effect on high energy photons(higher than 40keV). The single fiber simulation was extended to lens simulations for mammography use. Simulations for linear lenses and uniformly bent lenses are implemented.

A linear lens has straight channels with the channel size changing linearly. Linear lenses are expected to give the best transmission performance. However, the lenses available now are not perfectly linear. They are slightly curved. Curved lenses could provide extra magnification which is a advantage in mammography. But the transmission of a curved lens is usually not uniform. A profile of a lens is shown in Figure 4. To simplify the simulation, lenses are assumed to have a uniform curvature. A monolithic lens also does not have a fixed channel size. A further approximation also assumes the lens has a fixed channel size.

A linear lens simulation can be an extension of the straight fiber simulation. The transmission is simulated by sampling the capillaries in the lens with a small uniform step size. The bent lens is simulated as an extension of curved fiber. The simulation requires the bending curvature of each selected channel as an input. This value varies with the position of the channel.

Experimental and Simulation Results

Simulation for a Linear Lens

The advantages of a linear lens compared to a non-linear one include highest transmission and maximum transmission uniformity at the output end, which are important in mammography application. Perfectly linear lenses are not available at the current time, but its performance can be expected by simulation.

The lens focal spot is the source position at which the lens transmission is maximized. It is important to find the focal distance for a lens in practice. Focal distance can be found directly by maximizing the transmission of the lens. The success of this method depends on the stability of the x-ray source. According to the simulation, an alternative way to find the focal distance is to minimize the source scan angle, which is the full width at middle height of the source scan curve divided by the source to lens distance. This method is less affected by the source stability. The success of this method is proved by the measurement introduced in the next section. It is also found with simulation that, when the source is located at the focal spot, the transmission uniformity is more tolerant to the source movement in the direction perpendicular to the x-ray bean axis.

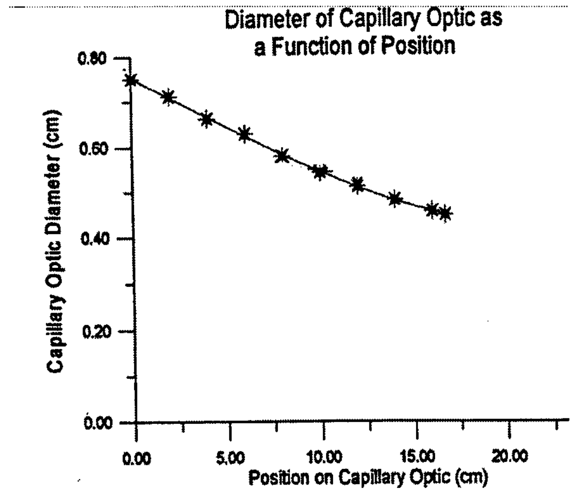

Figure 4 Profile of the measured lens.

Experimental and Simulated Results for a Non-linear Lens

A lens previously used in the test system for mammography was re-measured in an extended energy range. Its profile measured with a microscope is plotted in Figure 4. The lens is 166 mm long, tapering from 4.5 mm diameter at the entrance to 7.4 mm at the exit. The channel diameter is 15 μm at the entrance and 24 μm at the exit. The focal distance was measured to be 450 cm by both methods mentioned above. The experimental data was compared to the simulation results in Figure 5 and Figure 6.

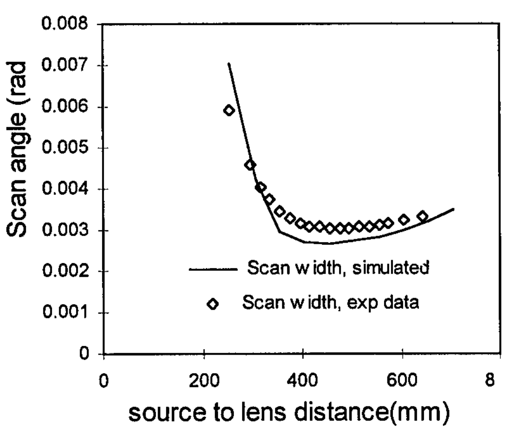

Figure 5 Scan angle as a function of source to lens distance.

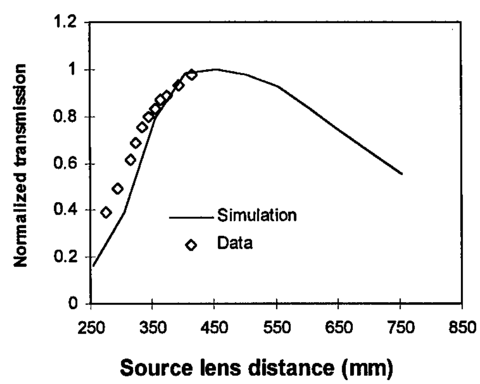

Figure 6 Normalized transmission as a function of source to lens distance.

They fit fairly well. As an approximation, the lens was treated as a uniformly bent lens in the simulation with outer channel bending curvature of 21 m. The simulation used the same roughness and waviness correction as that determined from a similar single capillary. The width of the scan curves were calculated with Gaussian fitting, and averaged over the two transverse directions.

Transmission was measured in a wide energy range for the whole lens as well as the central part of the lens. The transmission spectrum for the whole lens was plotted in Figure 7. The figure shows that the transmission drops quickly for photons with energy higher than 20 keV, but the transmission under 20 keV is almost flat. The low transmission at high energies can be explained by the non-linearity of the lens. Simulations plotted in Figure 7 and Figure 8 as the solid lines show higher transmission than the experimental results. This indicates that the lens has more reduction in transmission due to bending. This is expected, because the actual lens does not have uniform bending. The channels on the outer side of the lens have more bending than that at the central part, so they have low or zero transmission when the photon energy gets higher. This is consistent with the transmission measurement for the central part of the lens and the transmission uniformity measurement at different energies. Transmission of the central part of the lens was measured by putting a lead collimator before the lens. Transmission measured when the diameter of the collimator was 0.5 and 1 mm shows high transmission up to 80 keV in Figure 8. The transmission measured with the 0.5 mm collimator was even higher than that when the 1 mm collimator was used.

Transmission uniformity of the lens was measured at different energies and compared in Figure 9. At 8.4 keV, the whole lens transmits, although we can see the transmission is not flat due to the non-linearity and the defects of the lens. At 25 keV, transmission of the whole lens drops to 25% as shown in

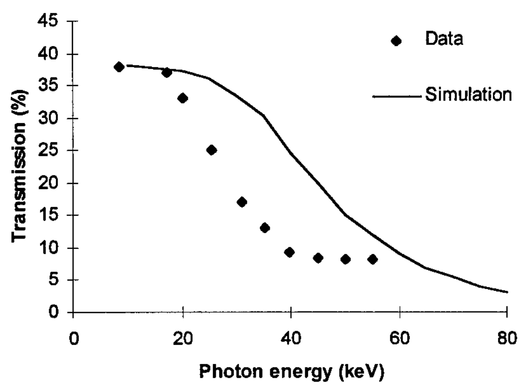

Figure 7 Transmission of the whole lens.

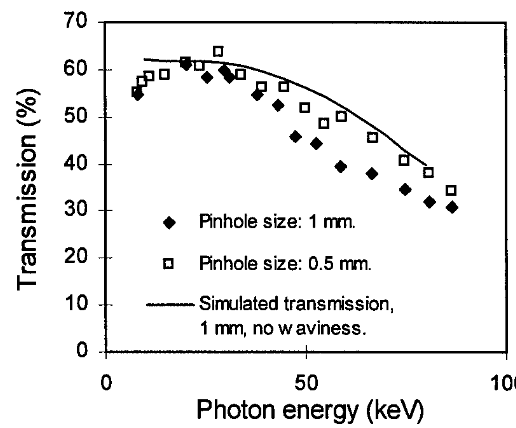

Figure 8 Transmission of the central part of the lens.

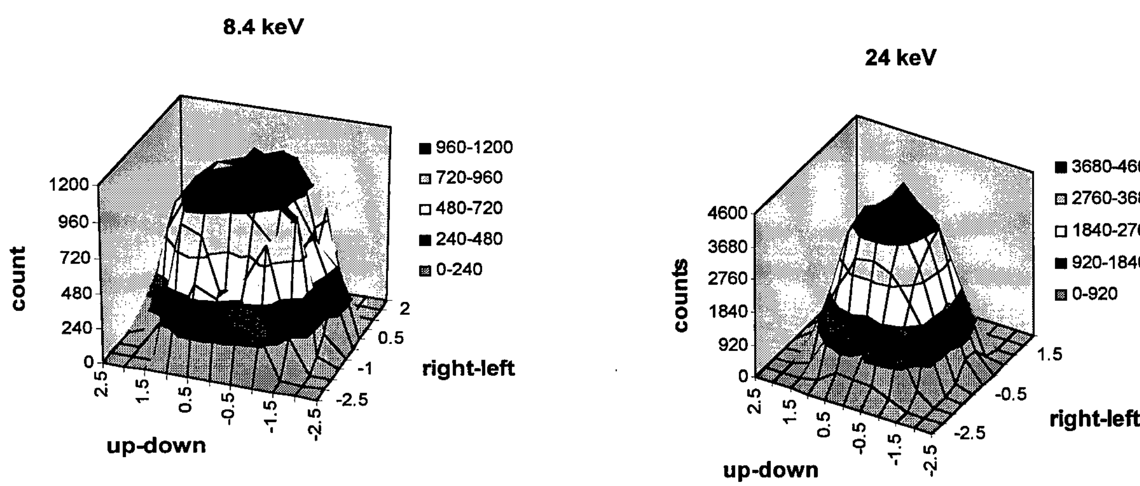

Figure 9 Transmission uniformity of the lens at 8.4 and 24 KeV.

Figure 7. The transmitting area is narrower at 24 KeV than that at 8.4 KeV in Figure 8. It is clear that the transmission drop is mainly caused by the lower transmission of the outer channels.

To summarize, the profile non-linearity is harmful in getting higher and uniform transmission. Most of the photons in mammography are around 20 KeV. If the lens analyzed above was as linear as its central part, transmission for the whole lens could be as high as 60% at mammographic energies. Therefore manufacturing of more linear lenses are necessary for mammography.

MTF Measurement

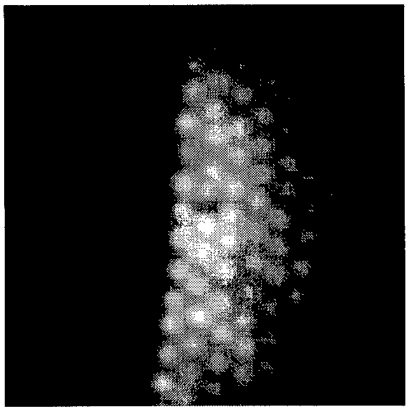

Figure 10 Magnified image of a lead edge. Real image size: 5(mm) X 5(mm).

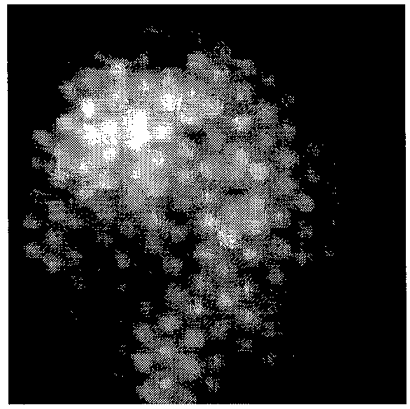

Figure 11 Magnified image of the background with lens structure. Real size: 5(mm) X 5(mm).

Capillary Structure Background Elimination

Modulation Transfer Function (MTF) is the most fundamental measurement of spatial resolution used in radiology. The standard technique is to image a slit, determine the line spread function (LSF) and compute the Fourier transform. The MTF measured for the mammography system with capillary optics, compared to that without the capillary optics, will give the resolution improvement. For some lenses, the transmission is not always uniform, as shown in Figure 11, which is an image of the output from a lens. The structure of the capillary bundles was obvious. In this case, the LSF could not be obtained by imaging a slit without background elimination. The background deducted slit image is the slit image devided by the image with capillary only. However, this involves image registration. The information for background that can be used for image registration is too little in the slit image. An alternative method is calculating the LSF as the derivation of the edge spread function (ESF). The edge image left enough background for registration. So that it could be a feasible method in our case.

A registration algorithm (FMI-SPOMF) proposed by Chen, et. al. [10] was used in this work. This is a method to match a two-dimensional image to a translated, rotated and scaled image. The approach consists two steps: the calculation of a Fourier-Mellin Invariant (FMI) descriptor for each image to be matched, and then matching of the FMI descriptors. FMI descripters are translation invariant. The matching of the FMI decriptors is to find out the rotation and scaling, and achieved using a symmetric phase-only matched filtering (SPOMF). In our case, there is no change in scaling, but rotation is probably involved. When the rotation was found, image translation is found by SPOMF method.

Images with and without edge are shown in Figure 10 and Figure 11. The edge was made of a lead plate. The size of each image is fifty by fifty in pixels. They were taken in an experimental digital mammography system with a computed radiography digital phosphor plate (CR plate). The digital CR plate has limited resolution, 5 lp/mm, and is usually considered to be not good enough for clinical mammography. But the effective resolution of the system could be improved by the magnification of the capillary optics. As introduced before, the capillary optic lens can provide magnification without introducing extra focal spot blur. The magnification of the capillary lens used in the system is 1.86, so that the effect resolution should be improved by a factor of 1.86.

The registration algorithm was implemented in IDL. With the FMI-SPOMF registration algorithm, no rotation was found. The translation was then found by SPOMF algorithm. The difference between the usual correlation method and SPOMF method is that it only use the phase information. The phase-only correlation function has sharper peak than normal correlation function. Sub-pixel resolution could be achieved theoretically. However it was found that the resolution is not good enough in our case. This may be caused by the relatively small image size. The background-subtracted result was further optimized by manual shifts in sub-pixel range. The result after manual optimization was shown in Figure 12. The periodic background is totally gone. A cubic spline interpolation method was used for the best result while shifting the background image relative to the edge image.

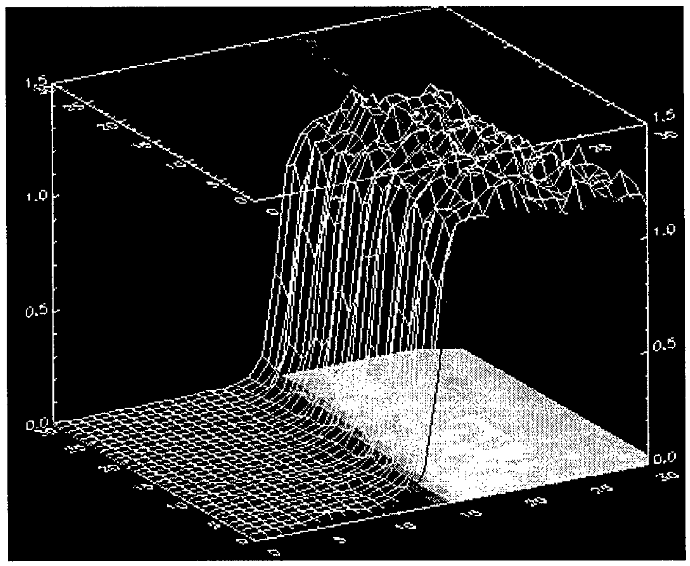

Figure 12 Three-dimensional edge image after background deduction.

MTF Calculation

The presampling MTF includes unsharpness of the detector and the sampling aperture. In order to eliminate the aliasing, a finely sampled ESF is obtained with a slightly angulated edge in a single exposure as illustrated in Figure 13.[11,12] The angle in our edge image in Figure 12 was calculated to be around 6 °. The resultant ESF was plotted in Figure 14. A direct calculation of MTF is to take the derivation of the ESF and result a LSF, then take Fourier transform. As it can been seen, the ESF in our case is not smooth enough for a direct calculation. An alternative technique is to use an ESF fitting procedure.[13] In the fitting method, the ESF is represented with a term (1-exp) and an error function (erf) as in equation (1). MTF is calculated by equation (2), where a, b, c and d are fitting parameters from equation (1). The fitting curve is plotted in Figure 14 as the solid line.

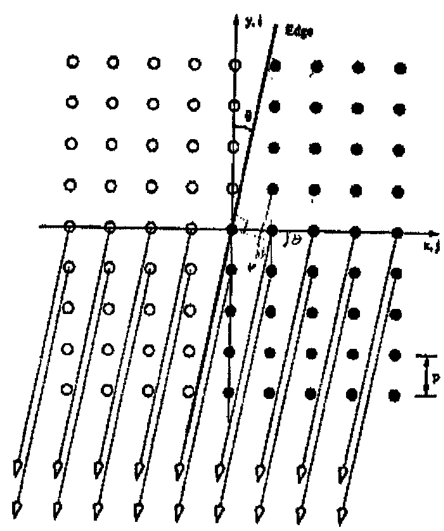

Figure 13[12] Reprojection of a two-dimensional edge image into a finely sampled ESF.

$$ESF(x) = a\{1-\exp(-b\,|x-x_0|)\} + c\cdot erf(d^{1/2}\,|x-x_0|) \quad (1)$$

$$MTF(f) = \frac{c\cdot\exp(-\pi^2 f^2/d) + a(1+4\pi^2 f^2/b^2)^{-1}}{(c+a)} \quad (2)$$

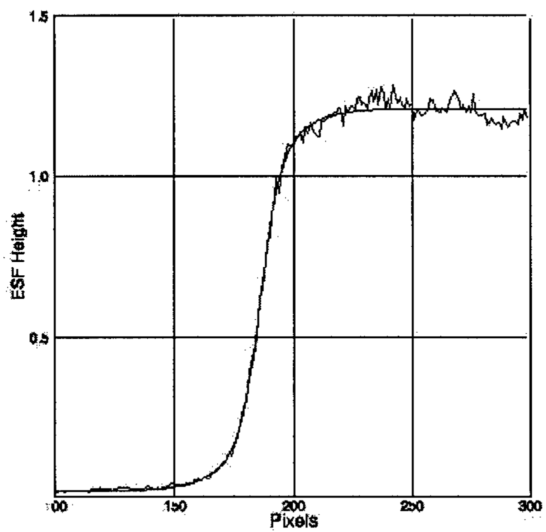

Figure 14 Edge spread function and its fitting curve.

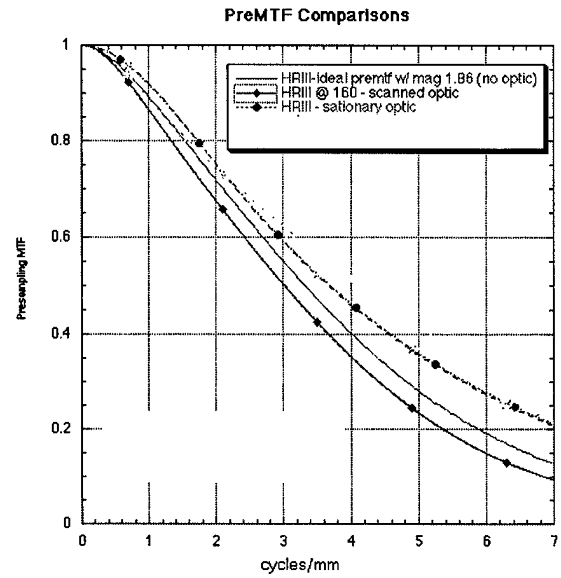

Figure 15 Calculated MTF compared with the MTFs with scanned optics, and without optics.

The calculated MTF was compared with that from scanned optics in Figure 15. The MTF from scanned optics was calculated from a slit image. Optic structure was smeared out with scanning, so no background deduction is necessary. An ideal MTF was also plotted in Figure 15. An ideal MTF is the one when we assume the lens only introduces the 1.86 factor magnification and no image degradation. It is measured with a slit image without optics, and its result was multiplied by the magnification of the capillary lens. The measured MTF with lens should no better than the ideal MTF. However, for some reason, the MTF for stationary lens is better than the ideal MTF. It is possible that the background elimination process failed the MTF measurement. Another possibility is that the magnification of the lens is different from 1.86, since the magnification was measured separately at a different time. More experiments are necessary to find out the reason.

Conclusion

A lens simulation has been developed based on the single fiber simulation. The simulation of a linear lens helped us to understand lens behavior and is helpful in lens measurement. The simulation with a non-linear lens explained the experimental data fairly well although it is based on a uniform bend approximation. The experiments and simulation in a wider photon energy range shows that the low and non-uniform transmission is mainly caused by the non-linearity. For practical use in mammography, developing more linear lenses is especially important. Measuring presampling MTF for a system with a stationary lens is difficult when the transmission is not uniform. A method using slightly angulated edge image with background elimination technique was developed. However, the measured result was better than the ideal case for some unknown reasons. There must be some thing wrong in experiments or calculation. Further work is necessary. Future work includes modifying the existing simulation, contrast and resolution measurement, and artifact investigation.

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